A Synthesis on the
Evolution of the Studded Tire

by

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A major report submitted in partial fulfillment
of the requirements for the degree of

Master of Science in Civil Engineering

University of Washington

1998

Approved by ______________________

Program Authorized
to Offer Degree Department of Civil Engineering

Date August 21, 1998

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

The author would like to express sincere appreciation to Professor Joe Mahoney for his support and assistance in the preparation of this manuscript. In addition, special thanks to the Staff at the Washington Department of Transportation (WSDOT) Library, as well as Ms. Linda Marsh of the WSDOT Materials Laboratory Library for the generous sharing of information/resources. I am also sincerely grateful and appreciative to the United States Navy, Civil Engineer Corps for providing the opportunity and financial support to participate in this program. Without the Navy's support, it would not have been possible to obtain this lifelong goal, to which the author is greatly in debt.

Last but not least, I am particularly grateful to my wife for her understanding and support that she gave me throughout this project, and to my two daughters who were my main sources of inspiration. Without their help and encouragement, I would not have been able to survive this project. I know they have endured many hardships throughout the life of this project and it is safe to assume that they are even more happy than I am to have it completed.

INTRODUCTION

Objective/Scope

Ever since studded tires were first introduced, the advantages, disadvantages, and effects of studded tires on vehicles, drivers and pavement systems has been the center of research and controversy for highway and transportation administrators, as well as safety engineers.

The primary objective of this synthesis is to assemble, extract, organize and present information pertaining to the history of the studded tire (i.e., how it has evolved over time) in a detailed/descriptive chronological manner. The project also explores the relationship between the wear of pavements and the studded tire developments that have taken place over the past forty years.

Both of these objectives were accomplished as a result of an extensive review of the literature, on a world wide basis, associated with the research of studded tires; their evolution, and wear of pavements, most of which were conducted during the period of 1966 through 1975. This project will also look at the new developments regarding studded tire features and their impact on pavement wear. The primary source of information on these recent developments is derived from the Scandinavian countries.

This project does not directly deal with the issues of performance of studded tires, the accident and safety aspects of the studded tire, nor does it deal with the cost associated with repairs of pavement damage caused by studded tires.

THE STUDDED TIRE – PAST TO PRESENT

Background

The origin of the studded tire concept can be traced as far back as the 1890's, when "metallic cleats" were being used in pneumatic tires. The purpose of these cleats was to increase wear resistance of the tires as well as provide better protection against damage while on the rough gravel roads of that time. However these cleats were short lived as a result of better roads and tire improvements [8].

The European and Scandinavian countries have been given credit for the initial market exposure of the tire stud to the driving public, which occurred in the late 1950's. The core of the first tire studs consisted of a small piece of tungsten carbide, which was about the thickness of a ten-penny nail (0.128 inches (3.2 mm)), had a length of approximately 0.313 inches (7.8 mm), and was held in place with a "jacket." As a unit, it was referred to as a "winter tire stud" [35]. Figure 1 represents the basic design of the first tire studs with tungsten carbide cores [8].

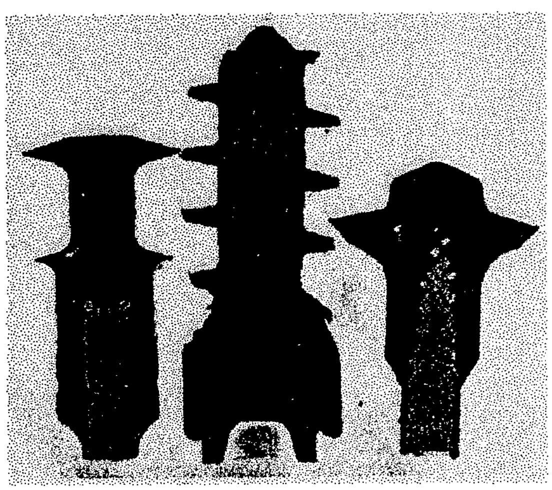

FIGURE 1. First tire studs with tungsten carbide cores [8].

Until the use of tungsten carbide as the core material, all previous attempts to develop anti-skid devices were unsuccessful. The success of the tungsten carbide core is the result of it being one of the hardest man-made materials available at that time. When manufactured to the proper specifications, and under normal driving conditions, it closely matched the wear rate of the rubber tire tread [35].

The jackets that hold the carbide core in place have been designed in various sizes and shapes and are manufactured from many different materials, such as low carbon steel, plastic, brass, aluminum and porcelain. The original flanges on the jacket body had numbered as high as four. A threaded shank similar to a screw was even used in place of the basic flange design [35], as is shown in Figure 1. Figure 2 represents the results of the initial fundamental research that led to a single-flange tire stud design, which was adopted by most of the world's tire-stud manufactures of 1964 [8].

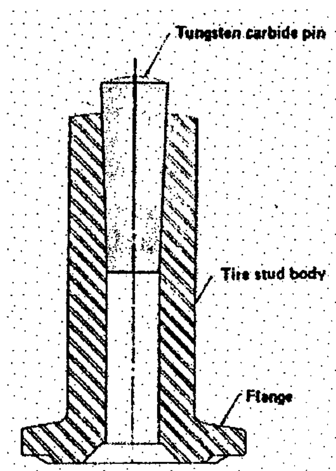

FIGURE 2. Cross-sectional view of single-flanged tire stud [8].

Initial Studded Tire Market

The single-flanged tire stud achieved its first substantial consumer acceptance and extensive use on automobiles in the 1961-1962 winter season in Europe, primarily in the

Scandinavian countries [43]. This strong consumer acceptance during the studded tires first season was very encouraging for tire stud manufactures. The speed of their acceptance was compared to the impact of the seat belt, and the aspect of safety was considered extremely important. By 1962, studded tires made up to 50 percent of the winter tire market in several Scandinavian countries [35].

Considering the European countries were having such favorable results with the studded tire acceptance by the driving public, the North American market was a natural progression for various manufactures to make. They viewed the North American market as having a potential many times greater than their existing European market.

The tire industry in Canada established a test market in the winter season of 1963-1964. It was estimated that 1.5 million tire studs were sold during that winter season, with 6 million being sold the following year, and by the end of the 1965-1966 winter season, sales of tire studs were estimated at over 25 million [35].

A limited test market was established in the United States during the 1963-1964 winter season. One of the first tire studs to be marketed in the United States consisted of a tungsten carbide insert with a bell-shaped plastic casing, and was called the Keinas-Hokken. The crude method of inserting these studs into the tires was one of the biggest problems at that time [35].

The life of the Keinas-Hokken was short lived however, and was soon replaced by an improved version made by the Scason Corporation, a European manufacturer. With the new version also came a more refined method of insertion. However, as marketing plans were being prepared, it became evident that numerous states had a law on their books which in general read: "Any block, stud, flange, cleat or any other protuberance of

any material other than rubber which projects beyond the tread will be illegal…"

Therefore, due to legal constraints within many states, the initial test market was confined to just two or three states, and as a result little was learned about the market's potential.

During the 1964-1965 winter season it was determined that thirteen states allowed the use of studded tires. Although it was later found to be inaccurate, they were determined at that time to be New York, Massachusetts, Ohio, Missouri, Maine, Maryland, New Hampshire, Tennessee, Vermont, Nevada, Connecticut, Kentucky, and Oklahoma [35].

The first three seasons of marketing studded tires in the United States showed a rapid increase in studded tire use, and is summarized in Table 1 [49].

TABLE 1. Increase in use of studded tires during the initial U.S. marketing period (1963 – 1966) [49].

Winter Season	No. Legal States	No. of States Marketed (legally)	No. of Tire Studs Sold in USA (millions)	Approximate No. of Tires (100 studs/tire)
1963-1964	13	2 – 3	3 – 5	30,000
1964-1965	13	13	25 – 30	250,000
1965-1966	28	28	250 – 275+	2,500,000

By the end of the 1965-1966 winter season, more than 30 states permitted the use of studded tires while some 18 states considered their use illegal. Figure 3 shows the states, except for Alaska, in which studded tires were allowed by the end of the 1966-1967 winter season [36].

There was clear evidence that the studded tire was gaining acceptance by the consumer, with estimates that an excess of half-a-billion studs would be sold during the 1966-1967 winter season [49]. During the period of 1965 to 1969, the annual sales of

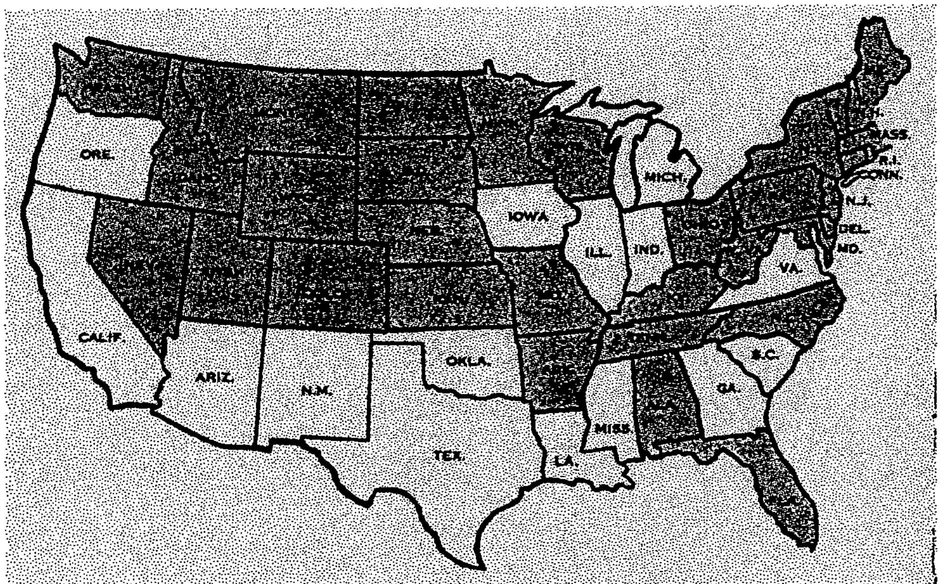

FIGURE 3. States (shaded), which allowed studded tires as of January 1, 1967 [36].

studded tires had increased threefold, with total sales estimated to be around 830 million in 1969 [42].

These estimates implied wide-spread, popular acceptance of studded tires as a winter driving aid by a significant proportion of vehicle owners in the northern states of this country where their use was legal at that time. It was reported that sales of studded tires might have been as high as 25 to 50 percent of the total snow-tire shipments during the 1969 – 1970 winter season [42]. This high level of use and acceptance by the general public had come about in spite of the numerous legitimate questions that had been raised regarding the performance of studded tires and their effect on pavement wear [43].

Studded Tire Use Rates

According to literature review, the current actual *use rates* are generally unknown in the United States and Canada [33]. The last time data was collected regarding the *percentage of vehicles in North America with studded tires* was in November 1972, when

a questionnaire requesting use estimates was sent to the 45 states which allowed studded tires at that time, as well as the Canadian regions, and Scandinavian countries. The five states, which did not allow the use of studded tires in 1972, were Minnesota, Utah, Mississippi, Louisiana, and Hawaii. Although the annual sales estimates demonstrated a continuing popularity for the studded tire, the primary concern of the highway engineers and administrators at that time was the total number of vehicles in North America with studded tires [42]. The data (historical in nature) collected on the percentage of vehicles in the United States, Canada, and abroad with studded tires is shown in Table 2 [49]. Estimates of studded tire use were reported as a percentage of registered passenger cars by 37 states and were unavailable from 8 states. Of these 37 states, 7 reported studded tire use at not more than 5 percent, with the remaining 30 states estimating usage within the range of 6 to 61 percent. This data was presumed to be indicative of the status of studded tire use in the United States in 1972 north of the 37th parallel, excluding Minnesota and Utah [42].

In general, the data showed that Sweden and Finland had higher rates of studded tire use than most North American states and provinces in 1972. Evidently, Finland was the only country, which had information comparing truck and car use at the time the data was collected [33]. The data also showed that the use of tire studs ranged from 0 to approximately 75 percent of all vehicles, with areas of harsh winters showing ranges from about 20 to 75 percent.

TABLE 2. Historical data on estimated percentage of studded tire use in 1972 [33].

Country	Agency	% of Vehicles with Studs	Agency	% of Vehicles with Studs
United States	Alabama	1	Montana	60
	Alaska	61	Nebraska	38
	Arizona	1	Nevada	6
	Arkansas	1	New Hampshire	30
	California	NA	New Jersey	20
	Colorado	30	New Mexico	NA
	Connecticut	25	New York	30
	Delaware	18	North Carolina	2
	Florida	NA	North Dakota	32
	Georgia	NA	Ohio	20
	Hawaii	NL	Oklahoma	1
	Idaho	27	Oregon	10
	Illinois	12	Pennsylvania	28
	Indiana	10	Rhode Island	NA
	Iowa	25	South Carolina	3
	Kansas	7	South Dakota	40
	Kentucky	12	Tennessee	NA
	Louisiana	NL	Texas	0
	Maine	NA	Utah	NL
	Maryland	NA	Vermont	60
	Massachusetts	32	Virginia	10
	Michigan	12	Washington	35
	Minnesota	NL	West Virginia	10
	Mississippi	NL	Wisconsin	20
	Missouri	14	Wyoming	35
Canada	Ontario			32
	Manitoba			20 – 25
	Quebec			50
	Maritime Provinces			50+
	Ottawa			48
Finland	Cars			90 – 95
	Trucks			40
Sweden				60

NA = estimate not available
NL = not legal

Allowed Use of Studded Tires

Ever since they were introduced in the early 1960's, the decision to allow the use of studded tires in the United States is something that has been constantly changing within each state over time. In 1963 it was estimated that only 13 states permitted the use of tire studs. Legislative action on the use of tire studs increased dramatically as a result of research, which was initiated by the states because consumer acceptance of studded

tires was on the increase. An estimated 28 states had legalized their use by 1965, and by the end of the 1966 – 1967 winter season, 34 states had legalized the use of tire studs. A great deal of research was performed from 1965 to 1967 on the impact/effect of studded tires on highway pavements. As a result, the trend for legalizing the use of studded tires had reversed by 1974, with tire studs being legal (without restrictions) in only 16 states, and permitted in 29 states (with restrictions) as well as the District of Columbia. There were only 5 states that actually prohibited the use of studded tires entirely [49]. Figure 4 represents the periods of which studded tire use was restricted in the United States and Canada in 1975.

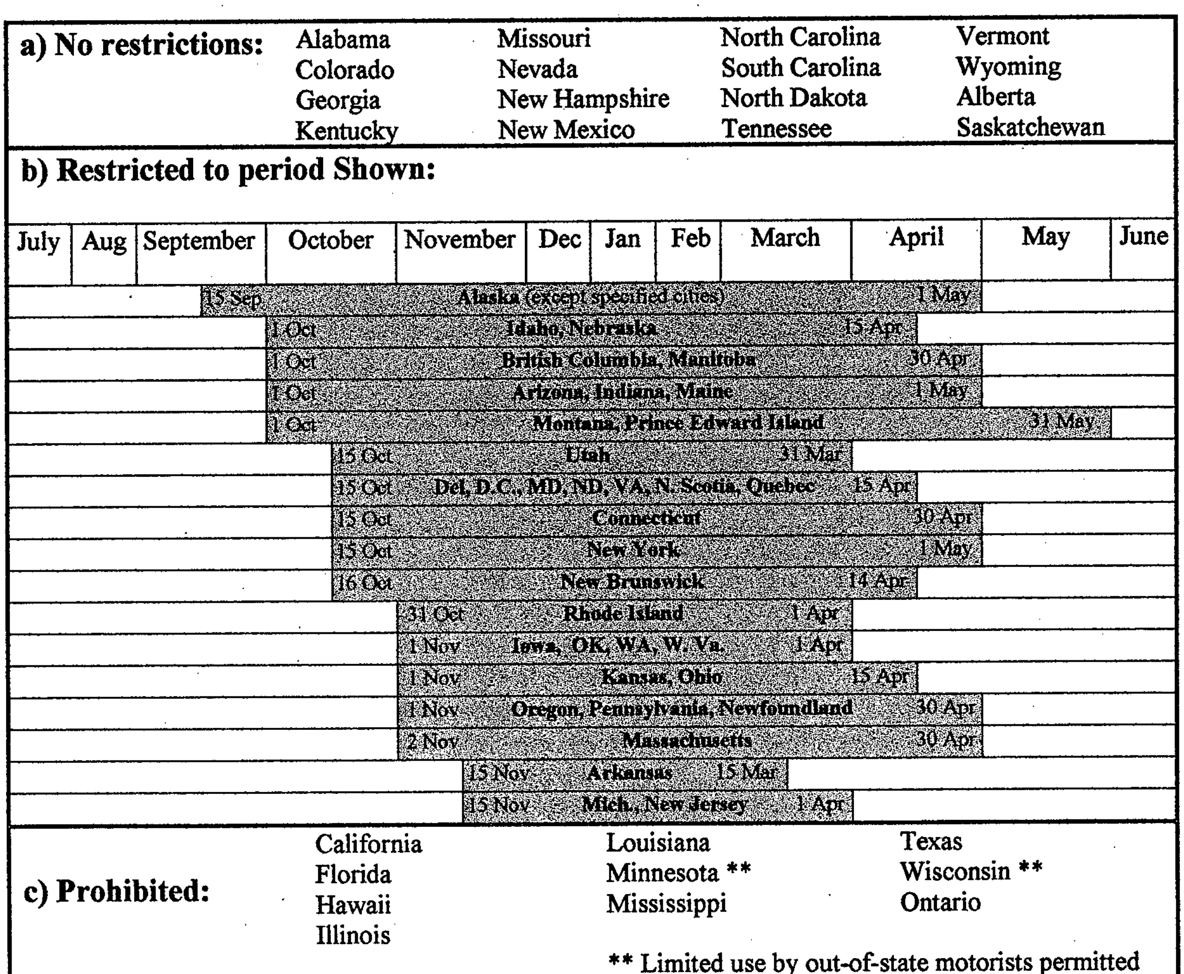

FIGURE 4. Legal restrictions on use of studded tires in 1975 [49].

Based on the literature review, Figure 4 basically remained in tact as one of the only complete listings of restrictions on studded tire use in the United States and Canadian provinces. This type of data would not be collected again until 1990 when the Alaskan Department of Transportation and Public Facilities conducted a survey of agencies regarding this issue [33]. The survey was sent to 30 highway agencies in the United States, 11 Canadian provinces and territories, and 4 foreign countries (Finland, Norway, Sweden, and the former West Germany). The results of this survey are shown in Table 3.

TABLE 3. 1990 Restrictions on use of studded tires [33].

US/Canada			
a) No restrictions	Colorado Vermont Saskatchewan	Note: Several other states outside the snow zone were not surveyed. These states may or may not restrict the use of studs.	
b) Restricted to time period shown	Alaska Connecticut Iowa Kansas Maine Nevada New Jersey New York Rhode Island Utah	(September 15 – April 30 (north of latitude 60° N) (October 1 – April 14 (south of latitude 60° N) (November 15 – April 30) (November 1 – April 1) (November 1 – April 5) (October 1 – May 1) (October 1 – April 30) (November 1 – April 1) (October 15 – May 1) (November 15 – April 1) (October 15 – March 15)	
c) Restricted (period unreported)	California Delaware Idaho Indiana Montana Nebraska	North Dakota Oregon Pennsylvania South Dakota Washington Wyoming	New Brunswick Nova Scotia Quebec
d) Prohibited	Arizona Illinois Maryland	Michigan Minnesota	Alberta Northwest Territories Ontario
Northern Europe			
a) No restrictions			
b) Restricted	Norway Sweden Finland	(Period unreported) (31 October to Easter) (1 November to 31 March)	
c) Prohibited	Germany		

In comparing the results of this 1990 survey with the 1975 data (Figure 4) it is evident that some changes occurred within that 15-year period. In 1975 Arizona, Maryland and Michigan permitted the use of studded tires during specific periods; however, the 1990 data shows that the use of tire studs was later prohibited in these three states. One state, California, went from being completely prohibited to being permitted, although the period of use was unreported. The 1990 data shows that there were minor changes made in the time periods of those states restricting the use of studs to a specific period. Most states chose October through April as their restricted use period, which reduced the permitted use period by one month for some. There was a tremendous change from the regions that had no restrictions. In 1975, 14 states and 2 provinces had no restrictions on the use of studded tires. However, the 1990 survey results show only three agencies (2 states and 1 province) as having no restrictions. This shift in restrictions is more than likely the result of extensive research that had been performed in the mid 1960's, but more specifically, the research throughout the 1970's on the negative effects of studded tires on highway pavements.

In an attempt to determine if any changes had occurred since the 1990 survey, another survey was conducted in 1995 for the Oregon Department of Transportation [4]. The survey was sent to 29 Northern states and 10 Canadian provinces to determine if policy or agency perceptions regarding studded tire use, and effects on pavement wear, had changed much since the 1990 survey.

The response rate for the northern states was over 86 percent, with 25 states responding out of the 29 surveyed. The response rate for the Canadian provinces was not as successful, with only four of the ten responding (40 percent). The results of the

survey, as they pertain to responses to the question regarding restrictions on the time of use of studded tires, are shown in Table 4.

TABLE 4. 1995 Restrictions on use of studded tires [4].

Unites States		
a) No restrictions	Wyoming Hwy Dept.	
b) Restricted to time period shown	Alaska DOT	(September 30 – May 1 (North of latitude 60° N)
		(October 1 – April 15 (South of latitude 60° N)
	California DOT	(November 1 – April 1)
	Connecticut	(November 15 – April 30)
	Iowa DOT	(November 1 – April 1)
	Kansas DOT	(November – April)
	Maine DOT	(October 1 – May 1)
	Maryland DOT	(November 15 – April 15)
	Michigan DOT*	(November 15 – April 15)
	Minnesota DOT**	(November 15 – May 1)
	Montana DOT	(October 15 – May 1)
	Nebraska Dept. of Rds	(November 1 – April 1)
	Nevada DOT	(October 1 – April 30)
	New Jersey DOT	(November 1 – April 15)
	New York DOT	(October 16 – April 30)
	North Dakota DOT	(November 15 – April 15)
	Oregon DOT	(November 1 – April 30)
	Rhode Island DOT	(November 15 – April 1)
	Utah DOT	(October 15 – March 31)
	Washington DOT	(November 1 – March 31)
c) Restricted (period unreported)	Colorado DOT	
	Delaware DOT	
	Idaho Trans.	
d) Prohibited	Illinois DOT	
	Indiana DOT	
Canadian Provinces		
a) No restrictions	Alberta	
b) Restricted	Manitoba	(October 1 – April 30)
	Nova Scotia	(Period Unreported)
	Quebec	(October 1 – April 15)
c) Prohibited		

* November 1 – May 1 in the Upper Peninsula and Northern Lower Peninsula.
** Studs were banned in 1972, but reinstated for rural mail carriers (only) in 1994.

As with the comparison between the 1975 and 1990 surveys, these results indicate that only minor changes had occurred in the time periods of those agencies restricting the use of studs to a specific period. Minnesota, which up until 1994 had banned the use of studded tires all together, now permits their use, but only for rural mail carriers [4]. The

state of Wyoming went from restricted use to no restrictions at all, while the state of Indiana went from restricted use to making tire stud use prohibited completely. There were also two states (Maryland and Michigan) that went from completely prohibiting the use of tire studs to allowing their use during a restricted time period. Assuming the 1995 survey results are current, out of the 20 states that responded to the survey, over 50 percent allow studs for 5.0 to 5.5 months out of a year, and typically start on October 15 or November 1 and end April 1 or April 15. The four Canadian provinces that responded (i.e., Alberta, Manitoba, Nova Scotia, and Quebec), currently allow the use of studded tires. One of these provinces, Alberta, went from prohibiting their use in 1990 to permitting their use with no restrictions.

Based on responses to other questions within this survey, it was determined that most of the states and provinces surveyed, have a perception that studded tire use is lower than past experience [4]. Additionally, the results showed that winter studded tire use has dropped to approximately less than 10 percent of all autos [4]. It is also interesting to note that mixed responses were received regarding agency perceptions of the effect of studded tires on pavement wear. There were fifteen respondents that identified a concern for studded tire pavement damage, while only ten respondents (i.e., 7 state's and 3 providence's) reported that they were not concerned [4]. These seven states were Colorado, Kansas, Maryland, Montana, New York, North Dakota, and Wyoming.

Tire Stud Characteristics

As mentioned earlier in this report, the original tire stud was developed in Scandinavian countries and then introduced to North America in the early to mid 1960's. Throughout the years, there have been numerous types of tire studs. However, as of

1972, only a few had been successfully marketed and used commercially. A list of the four basic types of tire studs, available in 1972, along with a brief description of their characteristics is shown in Table 5.

TABLE 5. Stud type and basic characteristics as of 1972 [26].

Stud Type	Basic Characteristics
Type I "Controlled Protrusion Stud"	• Carbide pin will move into stud body if protrusion is exceeded • 18 percent lighter in weight than conventional stud • 5 percent smaller flange than conventional stud
Type II "Perma-T-Gripper Stud"	• Pin found in other studs has been replaced with relatively small tungsten Carbide chips in a soft bonding matrix enclosed in a steel jacket • Designed to wear within 10 percent of tire wear, thus maintaining a protrusion of approximately 0.020 inches (0.5 mm) or less.
Type III "Conventional Steel Stud"	• Tungsten carbide pin • Stud protrusion will increase with tire wear
Type IV "Finnstop Stud"*	• Stud body made of lightweight metal or plastic with a tungsten carbide pin • Stud can be adjusted close to the tread rubber eliminating oscillation of the stud • Pin angle contact varies little with speed • Air cushion can be left under stud to reduce stiffness (floating stud) • Reduces heat build up between rubber and stud

*A plastic jacket stud.

The basic components of these tire studs consisted of two primary parts. The outside part of the stud is called a jacket or body that is held in the tire tread rubber by a flange at the base. The core/insert or pin is the element that protrudes beyond the tire surface and provides the contact with the pavement surface. Figure 5 is a diagram of a typical first generation tire stud that consisted of a 0.094 inches (2.4 mm) diameter tungsten carbide pin (i.e., the insert), which typically protruded 0.063 inches (1.6 mm) from its 0.188 inches (4.7 mm) diameter steel body (i.e., the jacket) [7]. This single-flanged tire stud design was adopted as the basic design by most of the tire stud manufacturers.

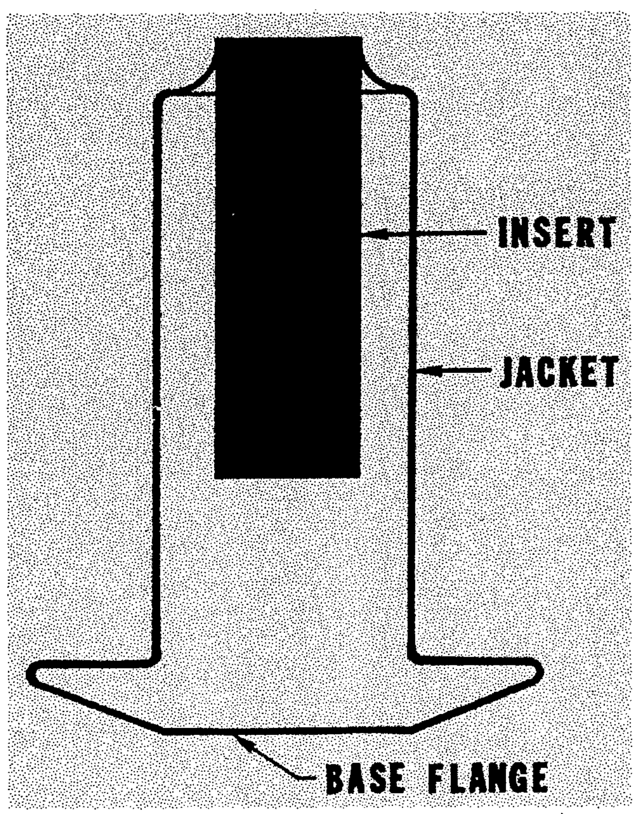

FIGURE 5. First generation single-flange tire stud [36].

The stud is held in place, within the tire during normal service, by the rubber around the stud exerting compression on the jacket [36]. It was reported that, once inserted properly, the force required to pull these units (i.e., the entire stud) out of the tread is about 90 pounds (400 Newton's). According to the literature, the centrifugal force acting on the stud is less than 2 pounds (8.9 Newton's), when the tire is traveling at 50 miles per hour (81 kilometers per hour) [35]. Given this information, once the stud is properly seated in the tire, speeds of over 500 miles per hour (806 kilometers per hour) would be required to create enough centrifugal force to eject the stud unit [35]. Evidently, a settling action takes place during the initial life of the tire stud. That is to say, the rubber begins to envelop the shape of the jacket. As shown by Figure 6, the rubber merely bridges the distance from the flange to the shank of the tire stud immediately after its insertion. The maximum retention of the stud in the tire is not developed until the

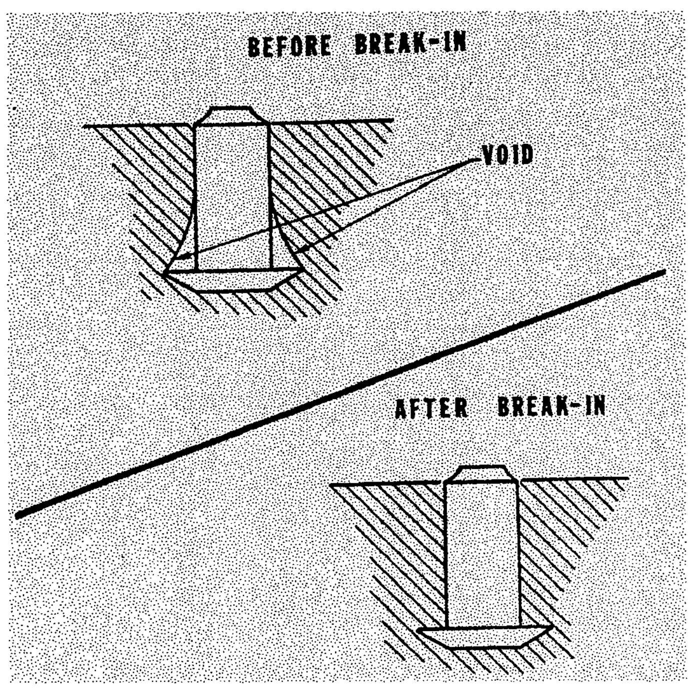

FIGURE 6. Tire stud before and after break-in-period [36].

rubber around the stud completely envelops the jacket [36].

It was recommended that before subjecting the studded tire to severe driving conditions, a break-in period of 50 miles (81 kilometers) at speeds less than 50 miles per hour (81 Kilometers per hour) be performed to allow the stud to seat itself in the tire properly, and insure maximum retention of the tire stud [36].

Since tire studs were first introduced, the stud flange diameter, and the hardness of the tungsten carbide pin, have both decreased with time in order to be more comparable with tire tread wear performance [4]. During the late 1960's and early 1970's, subsequent use of softer carbides were chosen to better match the rate of wear of the tire surface rubber, which also reduced the average tire stud protrusion length [49]. Table 6 displays the change in average tire stud protrusion from 1966 to 1972. These

TABLE 6. Change of average tire stud pin protrusion by year [8].

Year	Stud Protrusion (inches (mm))
1966	0.087 (2.2)
1967	0.081 (2.0)
1968	0.076 (1.9)
1969	0.074 (1.9)
1970	0.068 (1.7)
1971	0.065 (1.6)
1972	0.045 (1.1)

improvements to the tire stud were driven by pavement wear studies that revealed that stud protrusion length was a significant factor in pavement wear rates, and that stud pin protrusion increased as tire wear increased [4].

Research activities to develop a new stud design were intensified by the tire stud industry as the possibilities of a legal ban on the use of tire studs increased. A result of

this new research was the development and marketing, in 1972, of the "second generation studs" which were designed to control the amount of protrusion achieved by the pin beyond the tire surface throughout the life of the tire [49]. This stud became known as the "Controlled Protrusion" (CP) stud, and is graphically displayed in comparison with the first generation stud (i.e., the conventional stud) in Figure 7. The CP stud is 18 percent lighter and the flange is 5 percent smaller than the conventional stud [49]. It is designed with a tapered pin, which is allowed to move back into the stud jacket when the

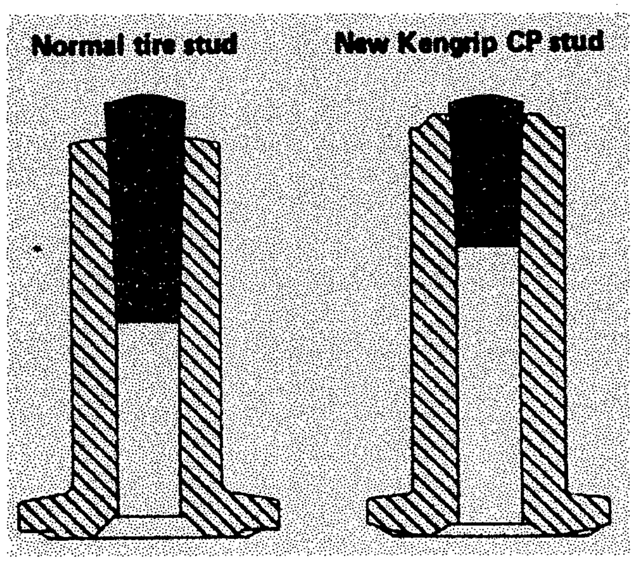

FIGURE 7. Comparison between the CP tire stud and the conventional stud [8].

dynamic force reaches a critical level [49]. The dynamic force is determined partially by the vehicle speed, but mostly by the tire stud protrusion length [8]. This means that these studs maintain a certain protrusion level almost independent from the wear resistance of the carbide insert and the tire, as well as driving conditions [4].

The critical minimum force necessary to move the pin is determined by the dimensions of the tapered pin and the shape and dimensions of the hole in the stud body

[8]. The tire stud protrusion is determined by this pin movement [8]. The average pin protrusion for these types of studs' ranged between 0.040 to 0.050 inches (1.0 to 1.3 mm), in 1972 [4]. At the time, this was approximately 30 percent less than the average tire stud protrusion associated with the conventional studs. The tests in 1972 showed that the new CP studs reduced pavement wear by 40 to 50 percent.

Another advantage of the CP stud is a reduction in heat caused by the impact of the tire stud on the pavement [8]. This means that the temperature between the stud and the tire tread is lower, which in turn eliminates the degradation of the of the rubber surrounding the stud [4]. All of which provided better stud retention capabilities.

The manufacturing of the CP stud went through further improvements in 1983, which resulted in additional weight reduction and improved protrusion characteristics as compared to the CP stud of 1972 [4]. It was reported that these improvements decreased pavement wear by as much as 50 percent when compared to the conventional studs [4]. The researchers also determined that radial tires with improved CP studs installed, reduced pavement wear to 75 percent of that previously recorded for bias tires with old conventional studs installed [4]. The literature search revealed that, in 1992, it was determined that only the CP stud is currently being used in the United States, and that the number of studs per tire generally ranges from 64 to 120 [33]. A graphical representation of the basic dimensions for the controlled protrusion stud in 1971 is shown in Figure 8.

Research and development to improve tire studs by reducing stud weight, increasing stud durability while decreasing pavement wear, has continued in the Scandinavian countries. As an example, research to investigate the pavement wearing characteristics of two new "lightweight" studs was being performed in 1992 by the

Swedish National Road Administration [4]. One of the lightweight studs tested consisted of a plastic jacket, weighing 0.7 grams (0.02 oz's), while the other stud consisted of a lightweight metal jacket, and weighed 0.95 grams (0.03 oz's). As a comparison, the older conventional studs weighed approximately 2.3 grams (0.08 oz's), and the controlled protrusion stud weighs 2.0 grams (0.07 oz's). The test results indicated that pavement wear is reduced by 50 percent when lightweight studs are used, as opposed to pavement wear caused by any of the early 2.3 gram (0.08 oz's) steel studs [4]. The differences in

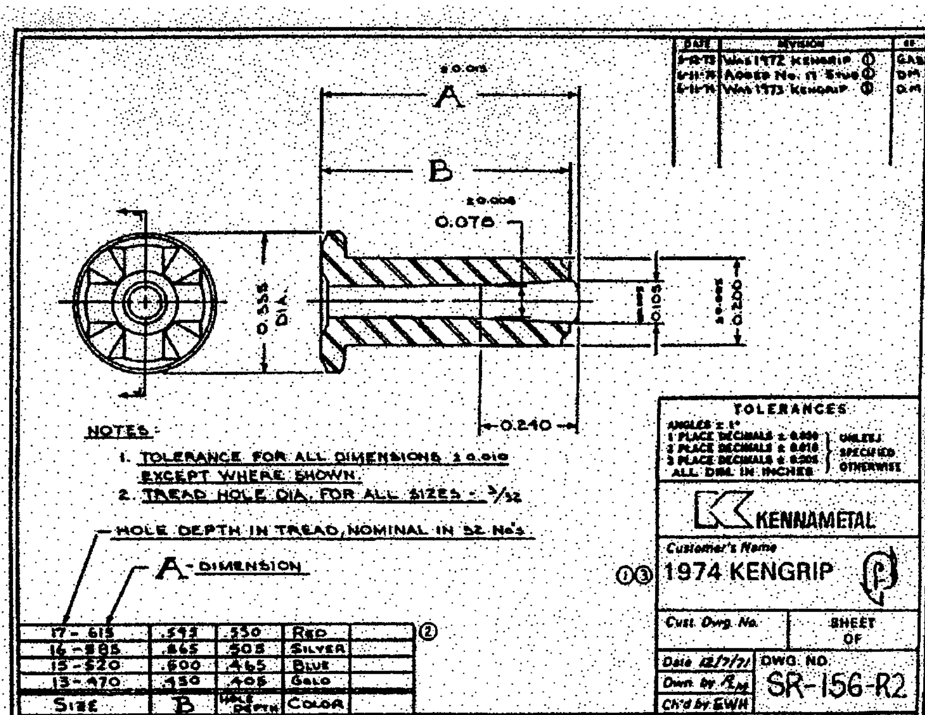

FIGURE 8. Typical dimensions for a controlled protrusion stud [49].

pavement wear between the two lightweight studs was small, however it was determined that the lightweight metal studs produced less pavement wear than the plastic lightweight stud, in spite of its heavier weight [4]. In addition to the pavement wear results, these

lightweight studs also displayed durability and pin protrusion characteristics similar to that of the controlled protrusion studs [4].

It is clear that the tire studs of today have evolved through dramatic changes since they were first introduced in the early 1960's. Specifically there are two major contributing factors to pavement wear that have seen significant improvements. The average stud protrusion length has gone from 0.087 inches (2.2 mm) in 1966 to a range of 0.047 to 0.059 inches (1.2 to 1.5 mm) in today's tire studs. This is close to a 40 percent decrease in protrusion length. Another major contributing factor of pavement wear is the average weight of the tire stud. It has also decreased substantially since the original studs of the early 1960's were first introduced. The recent tire studs in Scandinavia (i.e., the lightweight studs) are weighing in at about 1.1 grams (0.04 oz's), as opposed to the original conventional steel studs of the early 1960's, which weighed in at about 2.3 grams (0.08 oz's). This dramatic change has resulted in studs that are nearly 52 percent lighter today than what they were over three decades ago. However, the typical tire stud for passenger cars in the United States, currently weighs about 1.7 to 1.9 grams (0.06 to 0.07 oz's) [54], which is about 22 percent lighter than the older conventional tire studs.

In the United States, the size designation of the tire stud is based on a system derived by the Tire Stud Manufacturing Institute (TSMI). Although TSMI no longer exists, the tire dealers in the United States are still utilizing their sizing scheme today. As an illustration, a TSMI No. 12 stud means that the stud hole, in the tire tread, is 0.375 inches (9.4 mm) deep. In Europe, the stud manufactures use a different designation system to describe a stud. As an example, a stud in Europe might have a designation of "9-11-1", which means the studs head diameter is 9 mm (0.360 in.), the length of the stud

is 11 mm (0.440 in.), and the stud has 1 flange. This 9-11-1 stud is basically equivalent to the TSMI No. 12. Overall, approximately 85 to 90 percent of the tire studs currently sold within the United States are TSMI No. 11, 12, and 13, which are all used with standard size passenger car tires [54].

PAVEMENT WEAR IN GENERAL – PAST TO PRESENT

Cause of Pavement Wear

The results of the literature review showed that the common wear mechanism for pavements is by abrasive action of the stud due to the relative motion between tire and road. A report out of Finland in 1978 identified four main causes of studded tire pavement wear, and is summarized in Table 7 [4]. Considering no studies have been published that definitively establishes which cause has the greater impact, the debate continues over which mechanism is most important [4, 33]. The current belief in Alaska is that the primary cause or mechanism of studded tire wear is by scraping off the mastic and subsequent abrasion of the aggregate [4, 33].

TABLE 7. Cause of pavement wear under studded tires [33].

Cause	Description
1	The scraping action of the stud produces marks of wear on the mastic formed by the binder and the fine-grained aggregate.
2	The aggregate works loose from the pavement surface as a result of scraping by studs.
3	Scraping of the stud produces marks of wear on stone. Only in very soft aggregate does a rock fragment wear away completely by this action.
4	A stone is smashed by the impact of a stud and the pieces are loosened by the scraping action of the stud.

Pavement Wear Studies

In North America, most of the research regarding studded tire use and the impact on pavement wear was performed during the late 1960's and up through the early to mid 1970's. Most of what are known about studded tire use and their effects on pavements in North America was recorded during this era. This surge of research coincided with the use of conventional steel studs (i.e., the first generation stud). Some states within the

U.S. had performed their own research independently, while other states co-authored studies with bordering states.

These preliminary studies were undertaken to determine the amount of damage, which might be done to highway pavements by vehicles equipped with studded tires. Many of the early research studies had been carried out in the field as well as in the laboratory. However, it was later determined that this research was often performed with the end result being a lack of correlation between the two study approaches [4, 49].

The early (1965) field studies showed significant pavement wear from studded tires. However, because of time limitations, it was desired to obtain some general information as quickly as possible on the possible damaging effects of studded tires, and consequently no provisions were made to get quantitative measurements of the pavement wear damage [19]. Therefore, the results that were obtained were qualitative in nature [49]. These initial studies also showed that the wear was less on portland cement concrete pavements than on the bituminous pavements, and that most of the damage could be expected in areas where vehicles were braking or accelerating (e.g., intersections, curves, and tollgate lanes) [19]. However, the limited preliminary testing did not show any visual evidence of damage from constant-speed traffic [19]. On the basis of these 1965 tests, it was decided that there was not enough evidence that serious widespread pavement damage would result from the use of studded tires to withhold from the traveling public the potential safety benefits tire studs would provide [19]. It was recognized however, that additional data must be obtained due to the limited nature of any factual information on the abrasive action of the studded tires.

Laboratory studies performed in 1975, along with field measurements of actual pavement wear, confirmed the earlier findings. Unlike the previous studies, they were able to give quantitative values to wear rates in terms of inches of wear per million studded tire passes [49]. In many of the laboratory test programs there were special traffic simulators, comprised of circular test tracks. They were constructed to test the wear of various types of pavements against different studded tire applications. Unfortunately, however the diameter of these circular test tracks were typically not sufficient to prevent stud scrubbing action, which resulted in minimal direct correlation to actual traffic situations [4].

Overall, the number of pavement wear studies is limited. However, the literature review yielded some basic information regarding tests on pavement wear. Table 8 is a summary of tests performed in 1966 and 1967 on wear of pavement surfaces compiled from six different sources [22]. One source, Bellis and Dempster [3], had cautioned readers on the possible applications of their study results to locations other than New Jersey. It was well understood that variables of climatic conditions, traffic volumes, construction materials and methods, could be different in other areas of the United States. It was noted in Keyser [22] that "because [the] test parameters are not well defined, the results cannot be correlated." However, it was also determined that "the variability in the results obtained indicates that wear is a function of well-defined and limited conditions."

The literature search revealed a report [40] that compared the effects of pavement wear after one year without studs against the previous six-year period with studs. After six winters of legalized use in Minnesota (1965 to 1971), the 1971 legislature did not legalize studded tires for Minnesota residents for the 1971 –1973 biennium [40]. This

TABLE 8. Summary of tests (1966 and 1967) on wear of pavement surface by studded tires [22].

Vehicle	Load (Kg (lb.))			Studs		Tire Pressure (kPa)	Temp. (°C)	Speed (Km/hr) (mph)	Geometry	Track Width (cm (in.))	Volume of Wheel Passes	Contact Mode	Pavement Type	Wear (mm (in.))
	Front Wheel	Rear Wheel	Total	Front Wheel	Rear Wheel									
White and Jenkins, *1966* [55]														
Pickup	585 (1,300)	765 (1,700)	2,700 (6,000)	72	72	---	---	24 – 32 (15 – 20)	Straight	30.5 (12)	10,660	Normal	BC	6.3 (0.25)
								16 – 24 (10 – 15)	Curve, r =36 ft	46 - 61 (18 –24)	5,330	Acceleration	BC	2.8 (0.11)
												Deceleration	BC	4.5 (0.18)
Burke and McKenzie, *1966* [6]														
Auto	---	---	---	---	52	---	---	---	---	---	25	Rapid Start	PCC	1.0 (0.04)
Tessier and Normand, *1967* [22]*														
Auto	---	---	---	90	120	---	-18 to 4.4	88 (55)	Straight	91 (36)	33,500	Normal	BC	1.7 (0.068)
Lee, Page, and DeCarra, *1966* [30]														
Truck	1,575 (3,500)	1,800 (2) (4,000)(2)	10,350 (23,000)	110	110	---	-11 to 18	64 (40)	Straight & Curved	76 (30)	10,000	Normal	BC	2.2 (0.086)
													PCC	1.4 (0.054)
Auto	180 (400)	405 (900)	1,170 (2,600)	104	104	---	-8 to 19	64 (40)	Straight	76 (30)	10,000	Normal	BC	1.7 (0.068)
													PCC	0.45 (0.018)
Bellis and Dempster, *1966* [3]														
Auto	315 (1,400)	315 (1,400)	1,260 (2,800)	50 – 32	50 – 32	207 (30 psi)	---	32 max (20 max)	Straight	---	4,990	Normal acceleration	BC	0.65 (0.026)
													PCC	0.80 (0.032)
												Abrupt stop	BC	0.50 (0.02)
													PCC	0.25 (0.01)
												Emergency stop	BC	1.4 (0.056)
													PCC	0.38 (0.015)

* Data is from reference [22].
BC = Bituminous Concrete
PCC = Portland Cement Concrete

situation provided a rather unique opportunity for the Minnesota Department of Highways to record data on pavement wear during this period and compare it with data from the previous winters when studs were in use. Since tire studs were first legally introduced in Minnesota in 1965, the Minnesota Department of Highways (MDOH) had been making field observations and measurements on pavement surfaces in an attempt to determine the degree of wear associated with the use of studs [40]. Overall, they established 83 wear measurement sites that were distributed around all regions of the state in order to obtain a representation of various pavements, traffic volumes, and geographic locations [40].

These pavement wear measurements were continued on the previously established test sites following the statewide ban on studded tire use. In addition, MDOH established a number of new test points on several new pavement sections that had never been exposed to the previous volumes of studded tire traffic. This allowed pavement wear data to be collected the following winter of 1971 – 72 that solely represents the wear induced by normal traffic with sand and salt applications but with virtually no studded tire traffic. A summary of the results from a number of typical measurement points is shown in Table 9.

It is fairly evident from this data that after the 1971 – 1972 winter season, and with the ban on tire studs in effect, pavement wear was reduced to virtually zero [40]. Similarly, the report indicated that the results were the same on other test points throughout the state. These results confirmed the conclusions of all MDOHs previous studies that the pavement wear in Minnesota was unquestionably related to studded tire use [40].

TABLE 9. Depth of pavement surface wear in Minnesota at typical test points (inches (mm)) [40].

Winter Season	TP 6*		TP 33**		TP 32***		TP 83****	
	Yearly	Cumulative	Yearly	Cumulative	Yearly	Cumulative	Yearly	Cumulative
1966-67	0.04 (1.0)	0.04 (1.0)						
1967-68	0.07 (1.8)	0.11 (2.8)						
1968-69	0.07 (1.8)	0.18 (4.6)	0.09 (2.3)	0.09 (2.3)	0.10 (2.5)	0.10 (2.5)		
1969-70	0.05 (1.3)	0.23 (5.9)	0.07 (1.8)	0.16 (4.1)	0.03 (0.75)	0.13 (3.3)	0.08 (2.0)	0.08 (2.0)
1970-71	0.05 (1.3)	0.28 (7.2)	0.06 (1.5)	0.22 (5.6)	0.07 (1.8)	0.20 (5.1)	0.07 (1.8)	0.15 (3.8)
1971-72	0.00 (0.0)	0.28 (7.2)	0.00 (0.0)	0.22 (5.6)	0.00 (0.0)	0.20 (5.1)	0.01 (0.25)	0.16 (4.1)

*Test Point 6, portland cement concrete, gravel aggregate.
**Test Point 33, portland cement concrete, limestone aggregate.
***Test Point 32, asphaltic concrete, high type.
****Test Point 83, bituminous, intermediate type.

Table 10 represents a summary of some basic information on road wear studies, which was originally presented in a 1990 publication by Hicks et al., but were obtained from Lundy et al. [33]. These results in general indicate that

1. Reported wear rates, and the units used, varied considerably between highway agencies. Differences in wear rates are probably due to differences in materials and in percentages of vehicles with studded tires.
2. Pavement type has a great effect on pavement wear. Asphalt surfaces wear at a faster rate than portland cement concrete.
3. In areas of acceleration and deceleration, pavements wear increases substantially.

Considering all of the recent improvements that have been implemented in tire stud design and pavement mix designs, it should be noted that this information is not

TABLE 10. Historical summary of road wear studies [33].

Reference		Rate of Wear (in./passes)	Avg. Rate in inches (mm)/ 100,000 passes
a) **Literature**			
Quebec		0.25/100,000	0.25 (6.3)
Quebec	Acceleration	0.36-0.44/100,000	0.40 (10.0)
	Deceleration	0.18-0.20/100,000	0.19 (4.8)
	Normal	0.11/100,000	0.11 (2.8)
Germany		0.11/120,000	0.09 (2.3)
Finland		0.15-0.2/10,000 AADT	N/A
Sweden		0.5/40,000 AADT	N/A
Maryland		0.28-1.07/100,000	0.70 (17.5)
Minnesota		1.5/4,000,000	0.04 (1.0)
Oregon	Concrete	0.026/100,000	0.03 (0.75)
	Asphalt	0.066/100,000	0.07 (1.8)
b) **1990 Survey**			
California		0.0005-0.0018/1000	0.12 (3.0)
Connecticut		0.08/1,000,000	0.01 (0.25)
Maryland		0.028-0.107/10,000	0.68 (17.0)
New Jersey		0.05 per year for 5400 AADT per lane	N/A
New York		0.009-0.016/year PCC pavements 0.022-0.025/year ACC pavements	N/A N/A
Oregon		0.032/100,000 PCC pavements 0.073/100,000 ACC pavements	0.03 (0.75) 0.07 (1.8)
Norway		SPS* AC = 25 Topeka** = 15 Mastic stone = 10 – 15 PCC = 10	N/A
Sweden		35 g/vehicle (4 studded tires)/km driven	N/A

* SPS = g/cm (specific wear in grams worn out of the surfacing when a car with 4 studded wheels drives a 1 km distance).

** Topeka is a sand-rich hotmix.

considered representative of current tire stud wear. However, it is understood that the information contained in Table 10 can be used in a general manner and as a reference for further studies in this area [4]. With the exception of Germany, where studded tires have been banned since the 1974 – 1975 winter season, the European information in Table 10 is fairly recent for those countries reported, and reflects more up-to-date wear rates.

It is evident that the information available about pavement wear from studded tires is not always in the same format. Some researchers describe wear based on average annual daily traffic (AADT) or some choose to report wear based on a fixed number of studded tire passes. Still there are other researchers that report wear in terms of total number of passes. However, more recently in Sweden [9], pavement wear is assigned a weight in grams per vehicle per kilometer driven, and is called the SPS index for pavements. SPS is a Swedish abbreviation for specific wear and it indicates the actual wear from a certain amount of traffic from studded tires during a particular measuring period, usually one winter season [9]. Although they are considered to be reliable when making a forecast of the total wear of pavement in Sweden, it was pointed out that they do not provide an exact picture of pavement wear [9]. Nonetheless, the SPS index appears to be the reporting method that most Scandinavian researchers are utilizing when information on studded tire pavement wear is being reported [4].

In North America, there has not been substantial information published regarding studded tire pavement wear since the introduction of the improved Controlled Protrusion stud [4]. However, in 1990, the state of Alaska performed some research that resulted in the publishing of wear rates for asphalt concrete [33]. The wear rates are given for three sites in Juneau, Alaska, and the results are summarized in Table 11. The

wear rate was calculated by dividing the maximum rut depth by the estimated number of studded tire passes. The area of rutting was also measured, and the results were used to compute the total area of pavement surface loss. This information was than used to estimate the total weight loss per million studded tire passes [4].

TABLE 11. Juneau pavement wear per million studded tire passes [33].

Location	**Total Stud Passes by 4/91** (Million)	**Wear per Million Passes**		
		Wear Rate (inches (mm))	Wear Area (square inches (cm^2))	Tons/Lane/Mile & (Tone/Lane/km)
Juneau – Douglas Bridge:				
On Bridge	5.37	0.148 (3.7)	9.31 (60.5)	23.9 (13.5)
Before Bridge	5.37	0.134 (3.4)	9.92 (64.5)	25.5 (14.4)
Douglas Road	3.87	0.122 (3.1)	9.08 (59.0)	23.3 (13.1)
Mendenhall Loop	5.84	0.102 (2.6)	7.56 (49.1)	19.3 (10.9)

The rates of wear from this Alaskan study appear to be very consistent between the three sites, and they are considerably smaller than those shown in Table 10. The data collected at Douglas Bridge (before and on the bridge) shows a consistency in wear rate, which eliminates the possibility that subgrade deformation had contributed to the rutting [33]. Not surprisingly, it was also reported that pavement wear from studded tires is greater in the winter than in the summer season. However, although studs are not permitted during the summer season, it was estimated that about 10 percent of total wheel track rutting occur from studded tire use during the summer [33]. Additional research showed that the primary cause of this rutting was from small, lightweight vehicles equipped with studded tires [4]. This was determined by measuring the center-to-center distance between the wheel track rutting paths, which ranged from 1.4 to 1.5

meters (56 to 58 in.), and these measurements coincide with small, lightweight vehicles [4].

The Road Administration, Road Institute, and tire manufactures of Norway, Sweden and Finland have continued to perform extensive research on studded tires and their effects on pavement wear [2]. The Scandinavian countries approached studded tire wear in three related ways. The countries begun to pass legislation, which mandated the use of lightweight studs (studs that weigh less than 1.1 grams (0.04 oz's)). The core of these studs is tungsten carbide steel, but the jacket is made of plastic or lightweight aluminum oxide [2]. All of which reduces pavement wear rates by as much as 50 percent. Second they used a Stone Mastic Asphalt (SMA) concrete mix for surface courses, which contains up to 70 percent coarse aggregate [2]. It was found that the use of SMA could reduce pavement wear rates from 25 to 50 percent [2]. Third, they discovered a more durable aggregate that resisted tire stud wear at a higher success rate than aggregates from the local material source [2]. These harder aggregates consist of fine grained metamorphic and volcanic rocks. The use of these more durable aggregates has reduced wear rates by a factor of three to five as compared to their previous aggregate source. Some tests with SMA surfacing have also been conducted in Alaska as recently as 1996 with an overall result being a 45 percent improvement in pavement wear rate over the conventional pavement mixes [2].

Aggregate quality is the critical parameter that is of most importance to the wear-resistance of asphalt pavements to studded tires [17]. Today, in Sweden, the best pavements are about five times more wear-resistant than the pavements of the mid 1980's and possibly up to ten times better than those at the end of the 1960's [17].

Factors Affecting Pavement Wear

An excellent summary of the several factors that have been identified as affecting pavement wear rate was first prepared in 1970 by Keyser [22]. Keyser originally identified the characteristics for each factor (i.e., vehicle, tire, stud, pavement, environment, and traffic) that affect the rate of pavement wear. Keyser also identified the most important factors for bituminous pavement wear as wheel load, stud protrusion, temperature, and humidity. Table 12 represents a slightly modified version of Keyser's original summary. This modified table is the result of a more recent report [4], which based the modification on recent research from Finland. This recent research quantified the effects that each of the factors contribute to pavement wear and adds to the original list of characteristics for each factor [4]. The modifications included the effect that the type of tire (e.g., radial tire or bias ply tires), the stud flange diameter, vehicle speed, and the weight of the stud have on pavement wear.

Pavement wear factors include vehicle, tire, and stud system influences. The heavier the vehicle, the greater the increase in pavement wear. The performance characteristics of steel belted radials have proven to be superior to those of bias ply tires, thus inducing less wear to pavements when used with tire studs. Stud flange diameter also influences the rate of pavement wear. The force exerted by the stud on the road surface is directly related to the diameter of the stud flange. Studs having a small flange offer less resistance and are pushed back into the tire during their contact with the road [8].

TABLE 12. Factors effecting pavement wear [4].

Factor	Component	Characteristic
Vehicle, Tires, and Studs	Vehicle	▪ Type and weight ▪ Axial load ▪ Number of studded tires (front, rear) ▪ *Speed*
	Tire	▪ Type (snow or regular, *bias ply vs. radial*) ▪ Pneumatic Pressure ▪ Age ▪ Configuration of studs ▪ Number of studs
	Stud	▪ Type (material, shape) ▪ Protrusion length ▪ *Flange diameter* ▪ *Weight* ▪ Orientation of studs with respect to tire wear
	Stud wear vs. tire wear	
Pavement	Geometry	▪ Cornering (curves, sharp turns) ▪ Tangent Section ▪ Intersection ▪ Slope
	Surfacing material	▪ Type and characteristics (bituminous mixtures, surface treatment, precoated aggregate, chipping. Portland cement, hardness) ▪ Age
	Surface condition	▪ Surface texture and profile ▪ Icy ▪ Compacted snow (compactness) ▪ Sanded and salted icy surface ▪ Slush
Environment	Humidity, Temperature	▪ Wet, dry, humid
Traffic	Volume	▪ Number of passes and composition
	Speed	
	Wheel track	▪ Width; Distribution of wheel loads
	Contact mode	▪ Start (normal, abrupt) = spin ▪ Stop (normal, abrupt) = skid ▪ Acceleration (rate) = spin ▪ Deceleration (rate) = skid

The number of studs per tire has also been shown to be a significant factor in wheel path rutting. The number of tire studs used per tire has ranged over the years from

50 to 500 or more [35]. The latter, of course, represents an extreme situation, such as tires used in ice-racing. The number of studs per tire and road wear increase at a linear rate [8]. Unlike the United States, the number of studs per tire has been limited by most of the countries throughout Scandinavia. The allowable number of studs by tire size as determined by the Scandinavian Tire and Rim Organization (STRO) in 1997, is shown in Table 13. In the United States, the number of studs used on modern studded tires ranges from 64 to 120, dependent on the size of tire, with a typical average of approximately 100 studs [4].

TABLE 13. Allowable number of studs by tire size [50].

Tire Size (inches (cm))	**Allowable Number of Studs**		
	Finland	Norway	Sweden
13 (33)	90	90	90
14 – 15 (35.6–38.1)	110	110	110
> 15 (> 38.1)	130/PC* 150/CV**	150	130/PC 150/CV

*Passenger Cars
**Commercial Vehicles

The impact that stud protrusion length has on pavement wear has been recognized as an important studded tire performance variable because of an almost linear relationship between tire stud protrusion and dynamic force [49]. The protrusion length affects the energy absorbed by the pavement [43]. Thus, as stud protrusion increases so does the increase in road wear [8]. In 1966, tire stud protrusion was generally 0.087 inches (2.2 mm) and decreased to 0.065 inches (1.7 mm) by 1971 [8]. The development of the controlled protrusion stud in 1972 resulted in the possibility of average stud protrusion lengths ranging from 0.045 to 0.050 inches (1.1 to 1.3 mm) [4]. However, today, the

typical stud protrusion length is more in the range of 0.047 to 0.059 inches (1.2 to 1.5 mm) [4].

In 1992, a Swedish study examined the effects of vehicle speed on pavement wear, and determined that increased speed caused an increase in stud dynamic force, which directly impacts the pavement systems and hence increases wear [4]. These findings were also confirmed by a 1992 study performed in Finland [50]. The results of this study are presented in Table 14 with vehicle speed in kilometers per hour (km/h) and pavement wear in cubic centimeters (cm^3). These results show that the recent increase of

TABLE 14. Pavement wear due to vehicle speed [50].

Vehicle Speed (km/h (mph))	**Pavement Wear** (cm^3 (in^3))
50 (31)	0.20 (0.012)
60 (37)	0.23 (0.014)
70 (43)	0.27 (0.016)
80 (50)	0.32 (0.020)
90 (56)	0.42 (0.026)
100 (62)	0.56 (0.034)
110 (68)	0.78 (0.048)
120 (74)	1.19 (0.073)

Interstate rural speed limits in the United States from 89 km/h (55 mph) to 113 km/h (70 mph) has increased the potential for studded tire pavement wear by nearly a factor of two. That is to say, pavement wear could potentially increase from 0.41 cm^3 to 0.80 cm^3 (0.025 to 0.049 in^3) as a result of this higher speed.

In 1972, a study of pavement wear on a low speed (15 mph (24 km/h)) simulator determined that no difference in pavement wear could be found in similar studs of different weight. It was realized at the time that the reason for this was the low speed of the simulator. There was negligible variation in the dynamic force of studs with different

weight against the pavement, at a speed of 15 mph (24 km/h) [8]. According to reports from Finland, over the last thirty-five years pavement wear rate has been reduced by a factor of four by reducing the size and weight of the studs. It is important to reduce the weight because of the kinetic energy that is transferred at impact between the stud and the pavement [2]. This energy transfer picks at the aggregate and removes asphalt and fines [2]. The Technical Research Center of Finland (VTT) has performed extensive work in this area that was recently summarized in a 1997 report [50]. The results of this report show how stud weight increases pavement wear and are presented in Table 15 with stud weight in mass unit grams and pavement wear in cubic centimeters (cm^3). In comparing lightweight studs, weighing approximately 1.0 grams (0.035 oz's), to the results of a steel

TABLE 15. Pavement wear due to stud weight [50].

Stud Weight (grams (oz's))	**Pavement Wear** (cm^3 (in^3))
1.0 (0.035)	0.25 (0.015)
1.5 (0.053)	0.35 (0.021)
2.0 (0.070)	0.45 (0.027)
2.5 (0.088)	0.60 (0.037)
3.0 (0.105)	0.80 (0.049)

stud weighing approximately 2.0 grams (0.07 oz's), it was found that a reduction in stud weight resulted in about one-half the wear. Currently, the typical tire stud for approximately 85 to 90 percent of passenger cars in the United States (e.g., TSMI No. 11, 12, and 13 studs) weighs about 1.7 to 1.9 grams (0.06 to 0.07 oz's) [54]. There is a potential to reduce pavement wear by about 12 to 13 percent if a 1.5 gram (0.05 oz's) weight stud was to be adopted here in the United States. However, if some states decide to adopt the 1.1 gram (0.04 oz's) stud for passenger cars, the stud of choice for

Scandinavian countries, over the average 1.8 gram (0.06 oz's) stud, then there is a potential to reduce pavement wear by about 36 percent.

As mentioned earlier in this report, the pavement system itself is another factor that influences the rate of pavement wear caused by studded tires. It has been known for quite some time that portland cement concrete pavements are much more resistant to tire studs than asphalt pavements. The geometry of the road is also a contributing factor to where pavement wear occurs. As an example, tire stud wear on tangent sections of highways is significantly less [49] than that observed on sharp curves, where the studs tend to scrape the pavement and thus increase wear [4]. At areas where acceleration and deceleration occur, like at intersections, tire stud wear appears to be extremely concentrated. In one study it was determined that tire stud wear was 3.5 times greater at deceleration areas as opposed to tangent sections [22].

Not surprisingly, tire stud wear of pavements is influenced by the condition of the pavement surface, that is whether it is wet or dry, and whether there is ice or snow covering the surface. It is quite obvious, and it has been demonstrated that on snow and ice covered pavements, the use of tire studs will tend to cause less pavement wear than on bare pavement surfaces. However, what may sound surprising is that a wet asphalt pavement is worn down nearly twice as fast as when it is dry [4]. The effect of moisture conditions and pavement surface temperature on the development of tire stud rutting is graphically depicted in Figure 9.

The environmental factor of temperature also can influence the rate of studded tire pavement wear. In research performed by Cook and Kruker [27, 48], it was determined that the lowest wear rate for asphalt pavements occurs at or near 0 ° Celsius, with

increases in pavement wear rates at temperatures below and above 0 ° Celsius. This increase in pavement wear, as the pavement temperature goes below 0 ° Celsius is

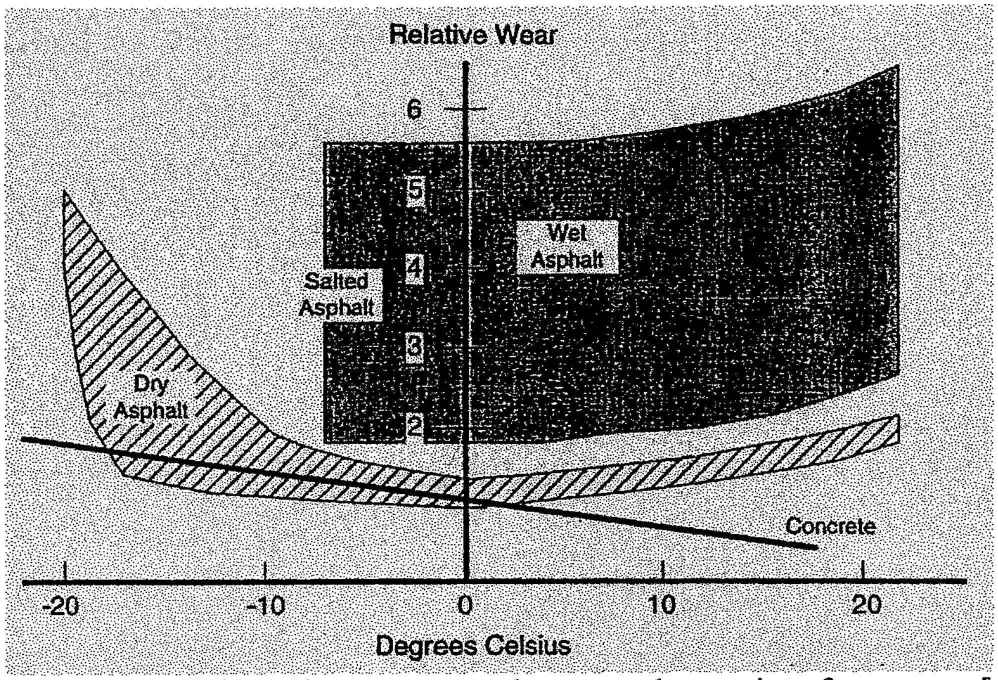

FIGURE 9. The effect of temperature and water on the wearing of pavements [4].

reportedly associated with an increase in tire hardness and pavement stiffness [33]. As the temperature of the asphalt pavement decreases, pavement stiffness increases, as does the force required to push the stud into the stiffer tire so that it is flush with the surface of the pavement [27, 48]. This means that for a given loading situation, more of the stud will protrude when the temperature is lower, which thus results in stud forces being higher. The possibility of increased wear rates is the result of this combination of high stud forces and increased pavement brittleness [27, 48]. The effect of temperatures on concrete pavements is much different than the effect on asphalt pavements. The rate of wear from tire studs is reduced on concrete pavements as the temperature increases [4].

CONCLUSIONS

Since their first exposure to the driving public nearly forty years ago in the European and Scandinavian countries, the tire stud has managed to survive numerous attempts by various highway agencies world wide, to completely remove them from the market as a winter driving aid. Although they offer motorists improvement of vehicle control on icy roads, studded tires have been criticized throughout the years by highway officials for their contribution to pavement wear.

The aggressive actions to potentially ban tire studs entirely, has resulted in research (into the actual effects that they have on asphalt and concrete pavements) to be performed within North America and Scandinavian countries since the mid 1960's. Almost three decades of research and debate on this issue resulted in numerous changes being made to improve the design of the tire stud as well as improvements to pavement compositions. As a result, the tire stud of today is likely to be perceived as being more acceptable from Scandinavian and North American highway agencies, compared to the past tire studs.

Two of the most recent changes in stud design that have contributed to this potential acceptance are a result of a nearly 40 percent decrease (i.e., from 2.2 to 1.3 mm (0.087 to 0.053 inches)) in stud protrusion length, and a 52 percent reduction (i.e., from 2.3 to 1.1 grams (0.08 to 0.04 oz's)) in the weight of the tire stud. Results over the past three and one-half decades concluded that pavement wear rates have been reduced more than four times by reducing the size and weight of the studs.

In the Scandinavian countries, improvements to pavement compositions (i.e., Stone Mastic Asphalt) have also resulted in a reported 25 to 50 percent reduction in wear rates. An additional key pavement wear factor is the speed of the vehicle. The Swedish and Finish studies of 1992 showed significant reductions in pavement wear as the speed of vehicles was reduced. Dropping speeds in the winter from 70 mph (113 km/h) to 55 mph (89 km/h) could decrease the potential for studded tire pavement wear by nearly a factor of two.

Overall, it may not be possible to eliminate pavement wear that is caused by the use of studded tires entirely. However, with the new tire stud designs of today, in combination with improved asphalt pavement compositions, it is possible to substantially reduce the problem of studded tire induced pavement wear.

REFERENCES

1. American Concrete Paving Association, Technical Subcommittee on Surface Properties, "Facts about Studded Tires," Technical Bulletin No. 18, August 1974.

2. Barter, T.D., Johnson, E.G., and Sterley, D.M., "Options for Reducing Stud-Related Pavement Wear," Alaska Department of Transportation and Public Facilities, September 1996.

3. Bellis, W. R., and Dempster, Jr, J. T., "Studded Tire Evaluation in New Jersey," Highway Research Board, Highway Research Record, No. 171, January 1967.

4. Brunette, B.E., "The Use and Effects of Studded Tires on Oregon Pavements," M. S. Thesis, Oregon State University, Corvallis, 1995.

5. Brunette, B.E., and Lundy, J.R., "Use and Effect of Studded Tires on Oregon Pavements," Transportation Research Record, No. 1536, 1996.

6. Burke, John F. and McKenzie, L. J., "Some Tests of Studded Tires in Illinois," Highway Research Board, Highway Research Record, No. 136, January 1966.

7. Burnett, W. B., and Kearney, E. J. "Studded Tires – Skid Resistance and Pavement Damage," Highway Research Board, Highway Research Record, No. 136, 1966.

8. Cantz, R., "New Tire-Stud Developments," Transportation Research Board, Highway Research Board, Highway Research Record, No. 418, 1972.

9. Carlsson, A., Centrell, P., and Öberg, G., "Studded Tyres – Socio-economic calculations," Swedish Road and Transport Research Institute, No. 756A, 1995.

10. Carlsson A., and Öberg, G., "Winter Tyres – Effects of Proposed Rules," Swedish Road and Transport Research Institute, No. 757A, 1995.

11. Cook, J.C., "Reduction of Pavement Wear Caused by Studded Tires," Washington State University, College of Engineering Research Division, Highway Research Section, April 1971.

12. Cook, J. C., and Krukar, M., "The Effect of Third Generation Tire Studs on Pavement Wear Reduction," 1977–1979. Report of Test Results on Pavement Wear from Various Tire-Stud Combinations, Washington State University, Report No. 79/15-27, June 1979

13. Creswell, J. S., Dunlap, D. F., and Green, J. A., "Studded Tires and Highway Safety - Feasibility of Determining Indirect Benefits," Transportation Research Board, NCHRP Report, No. 176, 1977.

REFERENCES
(continued)

14. Federal Highway Administration, "Studded Tires – An Update," Pavement Branch, January 1983.

15. Gustafson, K., "Pavement Wear from Studded Tires – the Swedish Solution," Swedish National Road and Transport Research Institute (VTI), 1997.

16. Jacobson, T., "Study of wear resistance of bituminous mixes to studded tyres – Tests with slabs of bituminous mixes inserted in roads and in the VTI's road simulator," Väg-och Trafik Institutet (VTI), No. 245, 1995.

17. Jacobson, T., "The wear resistance of bituminous mixture to studded tyres – the Swedish experience," The Swedish National Road and Transport Research Institute (VTI),No. 30, 1997.

18. Jacobson, T., "Wear resistance of bituminous mixes to studded tyres – A novel approach to field measurement and correlation with VTI's road simulator," Väg-och Trafik Institutet (VTI), No. 193, 1993

19. Jensen, P. A. and Korfhage, G. R., "Preliminary Studies of Effect of Studded Tires on Highway Pavements," Highway Research Board, Highway Research Record, No.136, 1966.

20. Kallberg, V., Kanner, H., Mäkinen, T., and Roine, M., "Estimation of Effects of Reduced Salting and Deceased Use of Studded Tires on Road Accidents in Winter," Transportation Research Record, No. 1533, 1996

21. Kennametal, Inc., "Studded Tires the Winter Winner," February 1985.

22. Keyser, J. H., "Effect of Studded Tires on the Durability of Road Surfacing," Ecole Polytechnique, Montreal, Canada, 38 pp., January, 1970, and Highway Research Board, Highway Research Record, No. 331, 1970.

23. Keyser, J. H., "Resistance of Various Types of Bituminous Concrete and Cement Concrete to Wear by Studded Tires," Highway Research Board, Highway Research Record, No. 352, 1971.

24. Keyser, J. H., "Mix Design Criteria for Wear-Resistant Bituminous Pavement Surfaces," Highway Research Board, Highway Research Record, No. 418, 1972.

25. Konagai, N., Asano, M., and Horita, N., "Influence of Regulation of Studded Tire Use in Hokkaido, Japan," Transportation Research Record, No. 1387, 1996.

REFERENCES
(continued)

26. Krukar, M., and Cook, J. C., "Studded Tire Pavement Wear Reduction & Repair – Phase I," Washington State Highway Department Research Program Report 9.1, (Transportation Systems Section Publication H-39), Washington State University; Pullman, Washington, December 30, 1972.

27. Krukar, M., and Cook, J. C., "The Effect of Studded Tires on Different Pavement Materials and Surface Textures," (Transportation Systems Section Publication H-36), Washington State University, Pullman, Washington, July 1972.

28. Krukar, M., and Cook, J. C., "The Effect of Studded Tires on Various Pavements and Surfaces," Highway Research Board, Highway Research Record, No.477, 1973.

29. Krukar, M., and Cook, J. C., "Studded Tire Pavement Wear Reduction & Repair – Phase II," Washington State Highway Department Research Program Report 9.2, (Transportation Systems Section Publication H-40), Washington State University; Pullman, Washington, July, 1973.

30. Lee, A., Page, T. A. and DeCarrera, R., "Effects of Carbide Studded Tires on Roadway Surfaces," Highway Research Board, Highway Research Record, No. 136, 1966.

31. Leppänen, A., "Final Result of Road Traffic in Winter Project: Socioeconomic Effects of Winter Maintenance and Studded Tires," Transportation Research Record, No. 1533, 1996.

32. Lu, J.J., "Vehicle Traction Performance on Snowy and Icy Surfaces," Transportation Research Record, No. 1536, 1996.

33. Lundy, J.R., Hicks, R.G., Scholz, T.V., and Esch, D.C., "Wheel Track Rutting Due To Studded Tires," Transportation Research Record, No. 1348, 1992.

34. Malik, M., "Preliminary Estimates for 1993 Studded Tire Pavement Damage," OregonDepartment of Transportation, Financial Services Branch, Economic and Financial Analysis unit, September 1994.

35. Miller, II, W. P., "The Winter Tire Stud," Highway Research Board, Highway Research Record, No. 136, 1966.

36. Miller, II, W. P., "Principles of Winter Tire Studs," Highway Research Board, Highway Research Record, No. 171, 1967.

REFERENCES
(continued)

37. Normand, J., "Influence of Studded Tires on Winter Driving Safety in Quebec," Department of Roads, Quebec, Highway Research Board, Highway Research Record, No. 352, 1971.

38. "Pavement Wear Due to Studded Tyres Run-over Wear Test," Technical Research Centre of Finland, Road Engineering and Geotechnology, 1996.

39. Peterson, D. E., Blake, D. G., "A Synthesis on Studded Tires," Materials and Tests Division Utah State Department of Highway, January1973.

40. Preus, C.K., "Studded Tire Effects on Pavements and Traffic Safety in Minnesota," Minnesota Department of Highways, Highway Research Board, Highway Research Record, No. 418, 1972.

41. Preus, C.K., "After Studs in Minnesota," Minnesota Department of Highways, Highway Research Board, Highway Research Record, No. 477, 1973.

42. Roberts, S. E., "Use of Studded Tires in the United States," Highway Research Board, Highway Research Record, No.477, 1973.

43. Rosenthal, P., Haselton, F. R., Bird, K. D., and Joseph, P. J., "Evaluation of Studded Tires: Performance Data and Pavement Wear Measurement," Cornell aeronautical Laboratory, Transportation Research Board, NCHRP Report No.61, 1969.

44. Smith, R. W. and Clough, D.J., "Effectiveness of Tires Under Winter Driving Conditions," Highway Research Board, Highway Research Record, No.418, 1972.

45. Smith, R. W., Ewens, W. E., and Clough, D. J., "Effectiveness of Studded Tires," Highway Research Board, Highway Research Record, No.352, 1971.

46. Smith, P., and Schonfeld, R., "Pavement Wear Due to Studded Tires and the Economic Consequences in Ontario," Report RR 152, Department of Highways, Ontario, Canada, November, 1969, and Highway Research Board, Highway Research Record, No. 331, 1970.

47. Smith, P., and Schonfeld, R., "Studies of Studded-Tire Damage and Performance in Ontario During the Winter of 1969-70,"Highway Research Board, Highway Research Record, No. 352, 1971.

REFERENCES
(continued)

48. Sorenson, H. C., Krukar, M., and Cook, J. C., "Studded Tire Pavement Wear Reduction & Repair – Phase III," Washington State Highway Department Research Program Report 9.3, (Transportation Systems Section Publication H-41), Washington State University; Pullman, Washington, December 31, 1973.

49. Transportation Research Board, "Effects of Studded Tires," NCHRP Synthesis of Practice 32, 1975

50. Unhola, T., "Studded Tires the Finish Way," Technical Research Centre of Finland, Communities and Infrastructure, 1997.

51. Washington State Department of Transportation, "Studded Tires," Maintenance & Operations Group, ISCORD 97, January 1979.

52. Washington State Department of Transportation, "Studded Tires – An Update," Pavement Branch, January 1983.

53. Washington State Highway Commission, "A Report on Studded Tires," Department of Highways, 1971.

54. Wessel, B., Memorandum: Information on Studded Tire Regulations, Stud Sizes, and Stud Weights, Bruno Wessel, Inc., November 1997.

55. White, O. A. and Jenkins, J. C., "Test of Steel Studded Snow Tires," Highway Research Board, Highway Research Record, No. 136, 1966.

56. Whitehurst, E. A., and Easton, A. H., "An Evaluation of Studded Tire Performance," Highway Research Board, Highway Research Record, No. 171, 1967.